RESEARCH ON A FERROACOUSTIC INFORMATION STORAGE SYSTEM

REPORT NO. 1

CONTRACT NO. NASw-592, AMENDMENT NO. 2

First Quarterly Report
for the period
June 10, 1964 to September 9, 1964

Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

WASHINGTON, DC

Prepared by

GENERAL DYNAMICS CORPORATION

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ROCHESTER, NEW YORK

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Report Prepared by

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PURPOSE: Analysis of the capabilities of ferroacoustic information storage for data processing systems, and investigation of advanced approaches to improve techniques and materials

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ABSTRACT

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Investigation of factors limiting the performance of a non-volatile, delay-line memory technique are reported. Model tests using thinner mill-processed storage media for the purpose of improving resolution and speed have been unsuccessful. Mechanical difficulties in coupling finer media to the associated ultrasonic transducer are believed to be the cause. Consideration of planar or strip line configurations, in place of tubular forms, indicates advantages for both near-term approaches using mill-processed media and long-range approaches using thin films. Improved techniques are described for providing more significant quasi-static measurements and analyses of the applicability of isotropic magnetic materials. Changes in media processing are indicated. Advances in procedures and new criteria for evaluating strain-sensitive anisotropic thin films for ferroacoustic storage are reported. Measurements conducted on an evaporated film are believed to show required basic properties.

Author

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1.0 INTRODUCTION

First quarter work under Contract NASw-592, Amendment No. 2, is a continuation of the investigation of the new memory technique reported in NASA Contractor Report[1] NASA CR-45 for the period ending 4 December 1963.

Ferroacoustic storage provides solid-state, non-volatile, updatable storage and non-destructive readout of information. Its basic capability for sequential access to data tends toward the low cost, size and weight per bit of information which characterize approaches using moving storage media such as magnetic drums or tape, but the usual associated mechanical problems are entirely avoided.

The technique uses the coincidence of a traveling strain pulse in a delay line, and a polarizing-field pulse applied axially, to accomplish write-in at any prescribed address. Subsequent ultrasonic pulses cause a readout voltage to be induced along the axis of the line as these pulses propagate through previously recorded regions non-destructively.

Studies[1] previously reported demonstrate that 20 db S/N can be achieved with a bit-pulse resolution of 3 microseconds using commercially available NiFe tubing with a 2-mil wall thickness, a ceramic transducer and a 1:10 pressure-transforming horn. When write-in bit data are applied axially, however, the large number of repetitions of polarizing field, which occur while filling the line with data, reduce the S/N to 8 db. Similarly, respective S/N ratios for 1-microsecond resolution are 15 db and 3 db. 3-microsecond and 1-microsecond resolutions correspond approximately to data rates of 330 kilocycles and 1 megacycle, respectively, and to linear bit densities of 2 and 6 bits per inch since propagation velocity is 0.17 inch per microsecond. An alternative write-in procedure, Mode 3[1] in which data are applied to the transducer and all data are standing on the line when a single application of polarizing field effects write-in, is proposed as one method for avoiding the creep in magnetization which reduces S/N with the original write-in procedure. Two-mil tubing driven directly, without an acoustical horn, would provide a usable S/N only under Mode 3 operation. Mode 3, however, is less versatile, and it introduces line-to-transducer coupling problems not yet solved.

Thinner storage media offer the direct approach to more rapid switching and avoidance of creep in magnetization. Commercially available drawn tubing or strip in ultra-thin gauges appear to promise the most immediately applicable media. Magnetic thin films deposited on a substrate having low acoustical loss have greater long-range potential, but development involves new basic problems associated with the requirement for enhanced strain sensitivity, as opposed to the minimization sought in magnetic thin films for conventional memories.

Optimization of magnetic material properties is needed to reduce both polarizing-field and transducer power. More important, however, are the limitations imposed on transducer design by the high stress which has been required to effect write-in with a usable S/N. Elimination of acoustical horns would reduce cost and size substantially, as well as technical variables such as dispersion, attenuation and reflections. Ultimate systems approaching the 100-MC range are expected to require peizoelectric-crystal or depletion-layer[2] transducers which provide much lower stress than the ceramic transducers found most suitable for the 1 to 10-MC range and, hence, will probably require a more strain-sensitive storage material. Optimization of material properties is also expected to improve S/N for given material uniformity under Mode 1 operation[1,3], in which data signals are applied as axial polarizing currents in the form of positive pulses to represent ONES and absence of pulses to represent ZEROS. Finally, improved material characteristics are required for Mode 2 operation, in which data signals are applied as axial currents with positive and negative pulses representing ONES and ZEROS, respectively; this is the only mode permitting random-access up-dating of information within a given line.

Current project objectives, summarized, call for systems analysis of near-term capabilities and long-range improvement of the ferroacoustic storage technique, including analysis and evaluation of magnetic storage materials, improvement of piezotransducer line-driving techniques, and analysis of factors affecting overall performance capabilities.

2.0 MEMORY CONFIGURATION

The three primary storage line configurations initially studied include (a) a tube of magnetostrictive material surrounding a separate axial conductor, (b) a single fine magnetostrictive wire serving both the magnetic-storage and electrical-conduction functions, and (c) a cylindrical magnetic thin film deposited on a non-metallic filament such as fused quartz to minimize acoustical attenuation.

Planar configurations being studied under the current project, using both mill-processed media and thin films, offer a number of potential advantages over cylindrical configurations. Rolled strip is commercially available in 50% NiFe down to a thickness of 1/8 mil, thus giving an effective thickness approximately one-tenth that for tubing or wire. Minimum sizes located to date in potentially suitable alloys, and their respective costs, are:

Material	Minimum Physical Thickness	Effective Thickness	Cost In Cents Per Foot
Tubing - 45 mil min. O.D. X 6 inch max. length	0.5 mil	0.5 mil	45.
Tubing - 5 mil O.D., min.	1.0	1.0	133.
Tubing - 10 mil O.D.	1.0	1.0	44.
Wire - 70% NiFe	0.7	0.35	0.077
Wire - 50% NiFe	1.0	0.5	0.075
Ribbon - 4.5 mil width	0.3	0.15	2.0
Strip - 1/32 inch width	0.125	0.06	3.0

Cost in terms of cents per bit of information should prove relatively more favorable for strip because of the higher linear bit density permitted by decreased thickness. Strip or wire can be coiled to provide a more compact package. Strips or ribbons can be stacked, separated by an insulating powder such as magnesia or alumina, can be annealed after stacking to remove strains caused in handling, and it is expected that the complete stack can then be bonded to a single transducer to provide parallel channels equivalent to those on a single drum or tape.

A configuration comprising thin-film strips deposited on a common low-loss planar substrate which is bonded to a single transducer offers major simplifications in fabrication by avoiding the need to handle and bond separate fine lines to a transducer without introducing excessive variations in mechanical impedance. Vacuum deposition of multiple lines becomes more practicable when a common planar substrate is used instead of separate cylindrical substrates. Similarly, electrodeposition on a planar substrate permits use of relatively straightforward stationary methods, whereas efforts to plate uniform films on fused-silica tubes of 30 mil O.D., as reported by Onyshkevych and Shahbender[(4)], for use in the sonic memory is requiring the development of a method using a precisely controlled traveling jet and rotating substrate.

Possible disadvantages of the planar configuration are a less uniform flux distribution in the transverse cross section and the longer flux path of a rectangular cross section if strip width cannot be reduced to values comparable with the diameters of usable circular cross sections. These disadvantages appear to be outweighed by the anticipated advantages, and current studies are therefore concentrated primarily on the planar configurations.

3.0 SUBSTRATE

The selection of a substrate material for thin films involves optimization of three primary factors: a) minimum acoustical attenuation, b) minimum temperature coefficient of velocity of propagation, and c) match between the temperature coefficients of expansion for substrate and thin film.

Minimum attenuation is provided by fused silica. Its temperature coefficient of expansion, however, is $0.6 \times 10^{-6}/^{o}C$ as compared with a representative value of $10^{-5}/^{o}C$ for 50% NiFe. The differential strain, ϵ, resulting is $9.4 \times 10^{-6}/^{o}C$, or approximately 10^{-4} inch/inch for a temperature change of $10^{o}C$. The corresponding stress in the film is

$$\sigma = Y\epsilon = 25 \times 10^{6} \times 10^{-4} = 2500 \text{ psi}$$

where Y = Young's Modulus = 25×10^{6} psi for 50% NiFe

This stress is of the same order as that required for write-in with present memory models and an order of magnitude higher than that anticipated for improved storage materials. Consequently, intolerable shifts in magnetic properties would result except in applications providing constant ambient temperature. It should be noted that this problem is avoided with drawn strip resting loosely on either a hard or resilient supporting member.

Review of data on the temperature coefficients of expansion for glasses shows that 50% NiFe can be matched approximately with a potash soda lead glass. Representative data for annealed alloys[5] and glasses[6], indicating the possibilities for achieving a suitable match, are as follows:

Alloy	Composition	Temperature Coefficient In ppm/°C 25° - 100°C	25° - 400°C
Carpenter "52"	51 Ni, Bal. Fe	9.95	10.0
Carpenter "49"	49 Ni, Bal. Fe	8.69	9.14
Carpenter "42"	42 Ni, Bal. Fe	4.63	5.65
Carpenter "45-5"	45 Ni, 6 Cr, Bal.Fe	7.60	10.00
Nicoseal	29 Ni, 17 Co, Bal.Fe	5.86	5.06

		-70° to 200°C
Carpenter Hi-Perm. "49"	49 Ni, Bal. Fe	5.8
Carpenter Hymu "80"	79 Ni, 4 Mo, Bal. Fe	12.9

Glass Type		Temperature Coefficient In ppm/°C
8871	Potash lead	10.3
1990	Potash soda lead	12.7
0120	Potash soda lead	8.9
7056	Borosilicate	5.1
7070	Borosilicate	3.2
8875	*Zero t/c glass	8.2
7940	Fused Silica	0.57

*Temperature coefficient of velocity at 25°C $\approx$ 0

Corning(7) gives attenuation figures (shear mode) of 0.15×10^{-3} and 6×10^{-3} db/μs-mc for the 8875 and 7940 materials, respectively. Mason(8) notes that shear and longitudinal attenuations per unit of delay are approximately equal in fused silica. The mean from several sources of data however, is approximately 0.3×10^{-3} and 7×10^{-3} db/μs-mc for fused silica and soft glass, respectively. Using the latter figures and assuming, e.g., that a loss of 2 db in the line can be accepted, comparative storage characteristics would be as follows:

	Substrate: Fused Silica	Substrate: Glass
Maximum line capacity	6670 bits	286 bits
Line length for 1-mc rate	129 feet	4.7 feet
Line length for 10-mc rate	12.9 feet	0.47 feet

The foregoing indicates that fused silica should be utilized in applications permitting close control of ambient temperature, but the 8875/0120 type of substrate will be required where temperature control is not permissible. In current studies directed toward optimization of magnetic material properties, glass substrates are used to reduce the variations in differential expansion which could otherwise prove troublesome even with laboratory temperature changes. Close match of temperature coefficients is not yet feasible, however, since composition is only temporarily established. It will also be necessary to determine whether thin-film temperature coefficients differ appreciably from the published data for bulk materials. Furthermore, there may be a major difference in the significance of temperature-induced orthogonal strains in the plane of the film versus the uniaxial strains required for write-in which have been used tentatively as the basis for comparison.

4.0 MAGNETIC MATERIAL PROPERTIES

4.1 Anistropic Films

The effect of applying strain to films with uniaxial anisotropy is treated in recent publications by Crowther[9] and by Mitchell, Lykken and Babcock[10]. Crowther shows that, in order to find the angle θ between the direction of magnetization and the unstrained easy axis, the expression for total energy

$$E_t = K_o \sin^2\theta + K_s \sin^2(\theta - \varphi)$$

can be differentiated, set equal to zero to find the equilibrium energy minimum, and solved for θ to give

(1) $\tan 2\theta = (K \sin 2\varphi)/(1 + K \cos 2\varphi)$

where φ is the angle between the applied strain and the unstrained easy axis, and $K = K_S/K_O$, the ratio of strain energy to the anistropy constant of the unstrained material. Further development leads to a normalized value of H_k, the new anisotropy field:

(2) $H_k/H_{ko} = (1 + K^2 + 2K \cos 2\varphi)^{\frac{1}{2}}$

where $H_{ko} = 2K_o/M$.

Equation (1) shows that strain applied along the original easy axis causes no rotation of the easy axis. However, the magnitude of the anisotropy field will vary with stress according to equation (2). Consequently, for ferroacoustic storage it appears worthwhile to consider configurations in which the easy axis is stressed, as well as the converse case where stress is applied in the hard direction and both write-in and readout occur along the easy axis.

Mitchell et al show a more detailed treatment and conclude, from the applications standpoint, that it will be impossible to make films of the same anisotropy on a commercial basis unless average magnetostriction is low (such as that provided by a composition of approximately 80% Ni-20% Fe). This may indicate that efforts to use uniaxially anisotropic films in ferroacoustic storage will prove impractical since high strain sensitivity is a basic requirement of the new technique. On the other hand, anisotropy does not appear to have the same significance in ferroacoustic storage that it has in conventional thin-film memories using coincident magnetic fields for switching.

The ferroacoustic technique as previously described[1,3] utilizes the increase in magnetization-curve slope which results from coincident stress. In isotropic materials this change corresponds to "magnetic softening" of the material which, in turn, would imply an accompanying decrease in coercivity, H_c. Pinch and Pinto[11] have published experimental results on the variation in Θ and H_k as functions of stress, which agree with the preceding reference for small stresses when angular dispersion resulting from the stress is small. They have also included data on the variation of H_c with stress in one example for a 77% NiFe film with $\varphi = 71^o$, and show that H_c follows H_k, but in a much less sensitive manner.

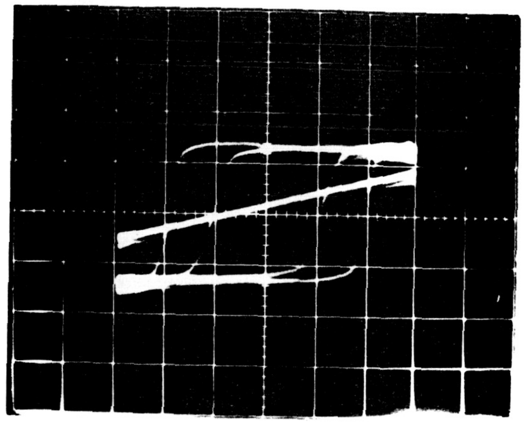
Data reported by Onyshkevych[12] for an electrodeposited film on a 30-mil OD fused silica tube show a decrease in H_c from 3.5 to 1.0 oersted, as measured in the circumferential direction, when axial tension is increased from zero to approximately 1 kg/mm^2. Photographs of the associated

B-H loops show, however, that as H_c decreases with tension the maximum induction B_m and the remanence B_r also decrease when H_{max} is held constant. Consequently, even though H_c is decreased by tension, this stress could not be expected to enhance the resulting remanence for a given polarizing field; furthermore, since the slope of the demagnetization curve is lower with tension applied, it appears that coincident stress would not enhance the reversibility of B_r for rewrite in the sonic storage technique. No loops for a compressive stress are shown.

During the subject project, instrumentation was completed to permit B-H measurements along either the hard or the easy axis with compressive or tensile stress along either axis. Planar films were investigated in accordance with the discussion of Section 2.

B-H characteristics for the eight possible test combinations were first explored using a vacuum-deposited film having negative magnetostriction near the 80% NiFe composition. Figure 1A shows B-H loops for zero stress and for compressive stresses along the hard axis when B is read along the easy axis. As compared with the preceding reference (for tensile stress applied axially to a magnetostrictively positive film), Figure 1A shows similar trends in the directions of change, but with a squarer loop and substantially less decrease in B_m and B_r when H_c has halved. Only if the addition of strain caused no decrease in B_r should the decrease in H_c with stress be expected to enhance the ease of reversing B, as desired for the rewrite operation.

B_r (2MV/DIV)



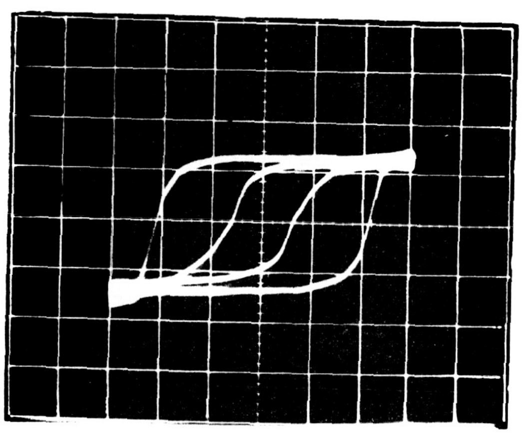
EASY AXIS OBSERVED
HARD AXIS STRESSED IN COMPRESSION

OUTER LOOP $\epsilon = 0$
INNER LOOP $\epsilon = 3 \times 10^{-4}$
CLOSED LOOP $\epsilon = 10^{-3}$

H (0.2 OE/DIV)

A

B_r (2MV/DIV)



HARD AXIS OBSERVED
EASY AXIS STRESSED IN TENSION

OUTER LOOP $\epsilon = 10^{-3}$
INNER LOOP $\epsilon = 0$

H (0.2 OE/DIV)

B

Figure 1. HYSTERESIS CHARACTERISTICS FOR 80% NiFe VACUUM-DEPOSITED FILM

The more pertinent data of Figure 2A show that, although B_r decreases monotonically for increasing stress at large H_{max}, there is an optimum stress which produces a very large increase of B_r when H_{max} is limited to lower values. In the case of this film with an applied field of 0.3 oersted, remanence due to polarizing field alone is zero whereas, with coincident stress, B_r is near the saturation remanence. Hence, data such as that of Figure 1A, the preceding referenced loops, or curves of H_c vs versus strain imply only negative results which appear to be confirmed by Figure 2A, but Figure 2A also shows the desired characteristics when applied field and strain are optimized.

Figure 1B shows the changes in B-H characteristics when tension is applied in the easy direction and induction is observed along the hard axis. In this case, H_c increases with stress, but, as shown by Figure 2B, remanence increases in the presence of stress for all values of H_{max}.

Hence, either tension or compression can greatly increase the remanence of an anisotropic film when the optimum values of applied field and stress are utilized. The film used in this investigation has considerable angular dispersion, as shown by the loop for the hard axis at zero strain in Figure 1B, rather than the ideal linear trace desired in coincident-current memories; the unstrained easy axis loop is the outer loop of Figure 1A. The strain sensitivity of the film is low, as should be expected with a composition near the point of zero magnetostriction. The composition was chosen for initial measurements to permit a more gradual transition from published work on anisotropic films which is

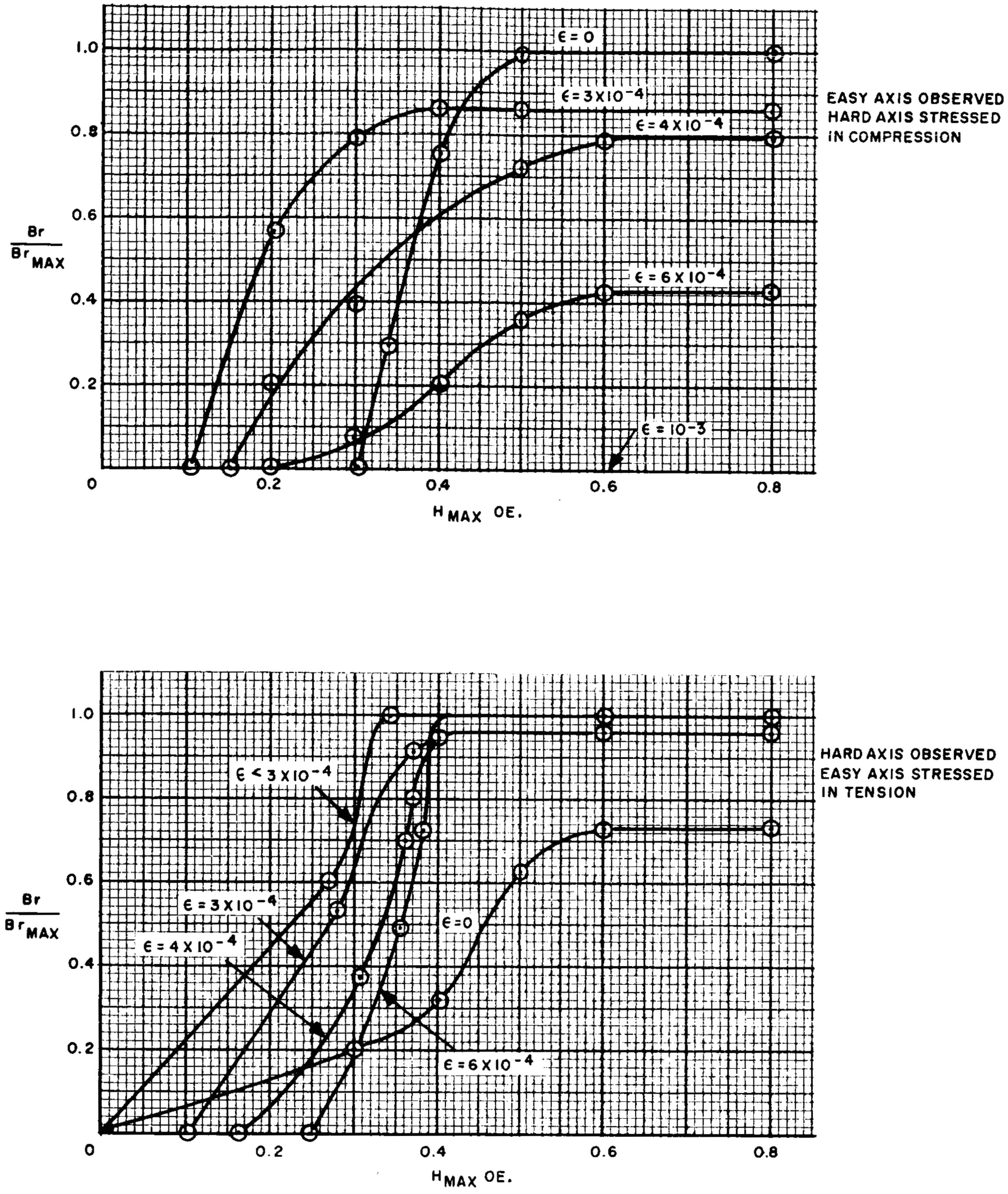


Figure 2. REMANENCE Vs. MAXIMUM FIELD FOR 80% NiFe VACUUM-DEPOSITED FILM

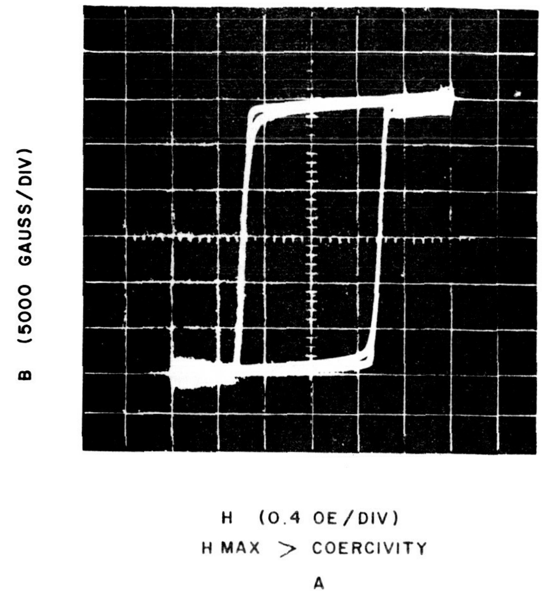
generally concentrated on materials of low magnetostriction.

A series of electrodeposited NiFe films of more suitable composition for ferroacoustic storage is being prepared. Strain calibration of test apparatus is currently limited to a minimum of 3×10^{-4} and revisions to provide for measurements at lower strains are being made.

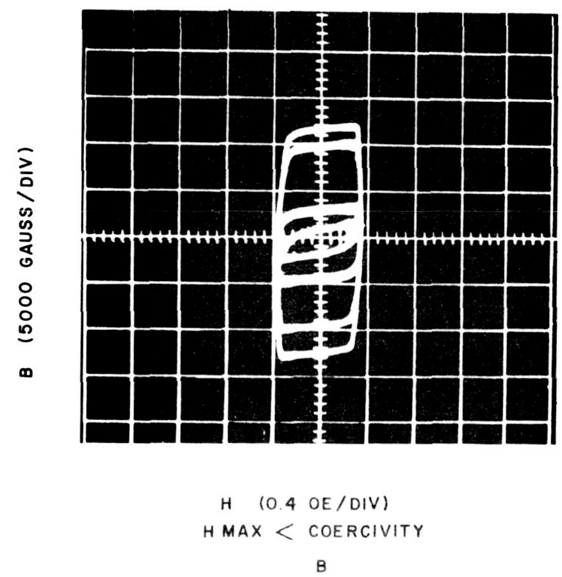
4.2 Grain-oriented Material

The ultra-thin strip discussed under Section 6.0 is the cube-textured material supplied under such trade names as Orthonol, Orthonik, Hypernik, H.C.R., and Delta-max by various concerns[13, 14]. The composition is approximately 50% Ni-50% Fe, the basic composition used successfully in tubular form in previous demonstrations of the ferroacoustic storage technique. This composition has a face-centered-cubic crystal structure with easy directions along the cube edges. Rolling and annealing processes are controlled to orient the crystals with cube faces in the rolling plane and cube edges in the direction of rolling, with the result that easy directions of magnetization are provided both longitudinally and trasversely.

The material, consequently, has a relatively square hysteresis loop and low H_c, as shown in Figure 3 for a sample measured in the longitudinal direction; similar characteristics in the trasverse direction have been assumed to date. The hysteresis loop appears more ideal than that of isotropic materials for storage purposes, and good strain sensitivity for 50% NiFe has been demonstrated previously. Nevertheless, it has been found impossible to produce a usable recording on half-mil Orthonol strip.



INNER LOOP $\sigma = 0$
OUTER LOOP $\sigma = 5500$ psi



INNER LOOP $\sigma = 0$
2ND LOOP $\sigma = 2200$ psi
3RD LOOP $\sigma = 3300$ psi
OUTER LOOP $\sigma = 5000$ psi

Figure 3. MAGNETIC CHARACTERISTICS OF ORTHONOL STRIP

The data of Figure 3 for B-H loops when longitudinal tension up to 5500 psi is applied show the material to be relatively insensitive to strain under these particular test conditions. Additional data are needed, however, for a satisfactory explanation of results.

A possible explanation requiring further study is that, after a cube-textured material has been subjected to a trasverse demagnetizing or erasing field, essentially all domains should be transversely oriented. Axial compression, which normally forces more domains into transverse alignment in an isotropic positive material, then could contribute little to steepen the magnetization characteristic of the cube-textured material. On the other hand, after transverse domain alignment the film has some similarity to a film with uniaxial anisotropy—for which case, Crowther's work[9] shows that stress can change the magnitude of anisotropy even when no rotation of easy axis occurs. Pending further study, it appears to be worthwhile to try a magnetic anneal to force quasi-uniaxial anisotropy and then operate under conditions discussed in Section 4.1.

4.3 Isotropic Materials

Initial material studies[1,3] in this program were concentrated primarily on isotropic materials, for which substantial progress was reported in the development of test procedures and interpretation of results. Magnetization or cyclic hysteresis curves, without and with fixed stress, were found suitable only for preliminary evaluations. Improvements in the precision of mechanical alignment for applying axial compressive stress to tubular material samples permitted measurement of small increases in the transverse induction of a 49% NiFe sample, however, no significant increase was obtained for a 50% NiFe sample which was otherwise outstanding in its sensitivity to changes in tension (Figures 4.21 and 4.22 of Reference 1). Curves of remanence, B_r, versus H_{max} showed approximately the same trends as the magnetization curves for B versus H.

Quasi-static measurements were then utilized to permit point-by-point study of the specific B-H-σ sequences which occur in the ferroacoustic storage process (Figure 4.25-4.27 of Reference 1). Most important was the discovery that readout strain sensitivity is not simply proportional to stored remanence; it is so strongly dependent on the previous history of H, σ, $\bar{\sigma}$, $\bar{H}$ that two different sequences were shown to produce equal strain sensitivities even through the average remanence differed in the ratio of 6:1. The significance of strain sensitivity ratios can be appreciated by reference[3] to the analysis under "Signal-To-Noise and Output Criteria" which explains the need for ratios of 2:1 and greater for one and zero recordings. The detailed measurements previously reported concerning the effects of sequence were limited to one sample, namely the 49% NiFe sample which was selected for initial study because its magnetization curves had shown the best changes under compressive stress.

During the past quarter, test procedures and a form of data presentation for isotropic materials have been found which appear to be fully indicative. As shown in Figure 4, readout strain-sensitivity

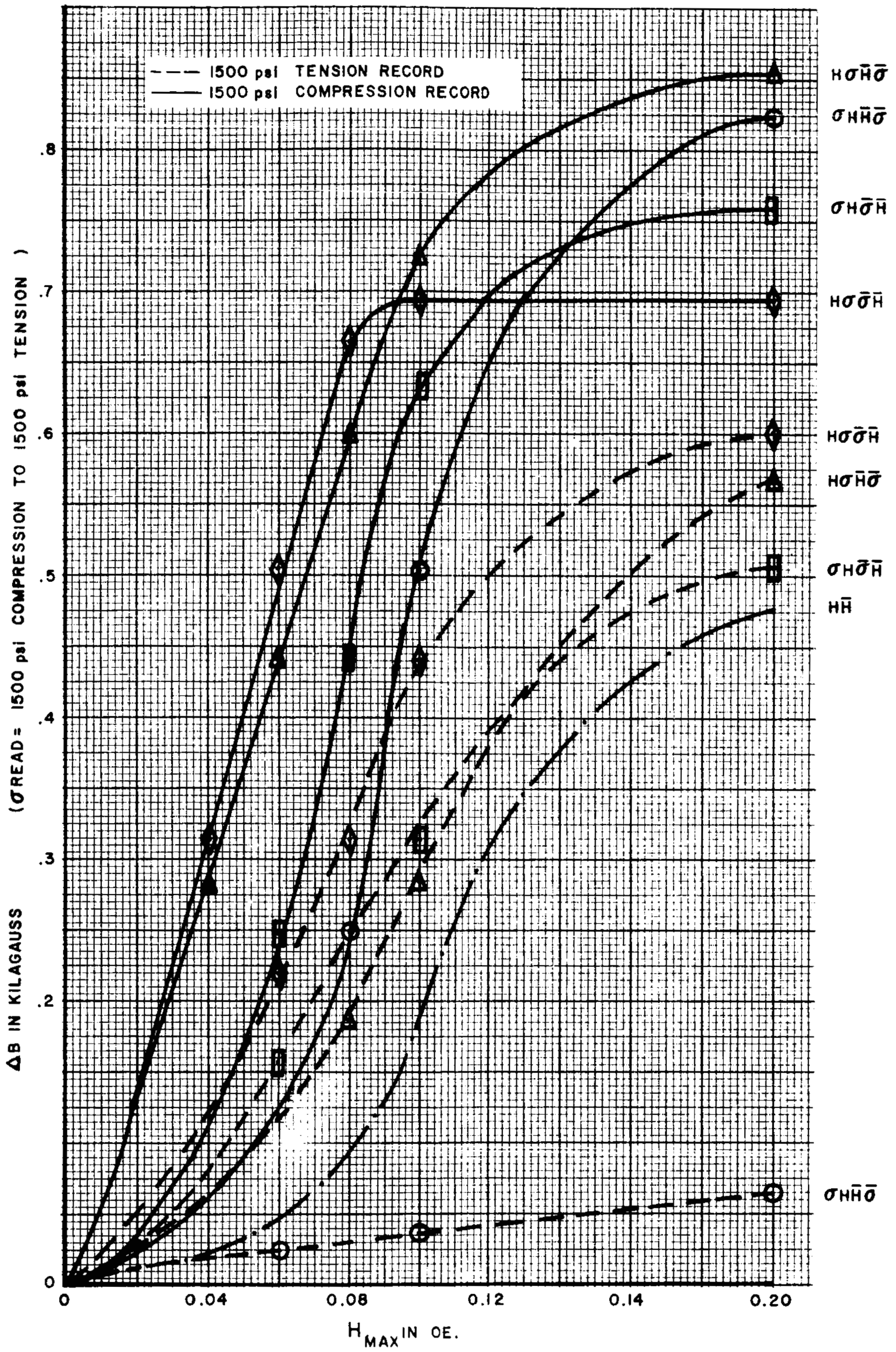


Figure 4. STRAIN SENSITIVITY OF FULLY ANNEALED 50% NiFe AS A FUNCTION OF MAXIMUM FIELD AND WRITE-IN SEQUENCE

is plotted as a function of write-in field intensity for each of the possible write-in sequences. Readout strain sensitivity is the change in remanence ΔB_r resulting from a change in stress $\Delta \sigma$. The same peak values of stress are used in the write and read operations. The $H\bar{H}$ sequence corresponds to ZERO write-in whereas the sequences involving stress are alternative ONE write-in sequences.

Figure 4 for fully annealed 50% NiFe indicates excellent ferro-acoustic storage properties. The ratio of readout strain-sensitivities approximates 12:1, e.g., for the $H\sigma\bar{\sigma}\bar{H}$ and $H\bar{H}$ sequences, when write-in H is 0.04 oersteds. To obtain these results, further improvement in the alignment of samples was found necessary in order to optimize performance with axial compression. Even with the improved alignment, however, simple magnetization curves for the sample in fixed axial compression show no increase in slope relative to the curves for the unstressed sample. Mechanical alignment of samples for static measurements clearly becomes increasingly difficult as sensitivity is increased by annealing and optimization of composition. Previously reported unsuccessful efforts to record dynamically on fully annealed 50% NiFe appeared to correlate with the negative results of the original static data for that material and the emphasis of work was consequently shifted to harder materials for which usable dynamic results were demonstrated. In view of the superior results indicated by Figure 4, a new model with a line of 50% NiFe annealed at 2100°F has been constructed and is ready for dynamic tests.

Figure 5 shows quasi-static data for 50% NiFe annealed at 1000°F and tested in accordance with the new procedures described with reference to Figure 4. Interest in the low-temperature anneal resulted from circumstances encountered with the thin-wall tubing supplied for models. Mill processing of the 50% NiFe used in previously reported successful model tests included a final straightening operation following anneal at 1700° - 1750°F. In the belief that uniformity could be improved by eliminating the final straightening, a 1000°F laboratory anneal for the cold-drawn material was established which provided B-H loops and magnetization curves closely approximating the characteristics of the straightened material. Comparison of Figures 4 and 5, however, shows that best strain-sensitivity ratios for the 1000°F anneal are only about one-sixth those for the 2100°F anneal. Dynamic model tests for the corresponding thin-wall tubing are discussed under Section 6.0.

Static data for 70% NiFe annealed at 2100°F were also obtained using the new procedures. Strain-sensitivity ratios were less than 2:1 for all but very low values of H. Strain-sensitivity amplitude even for the highest remanence was only 20% that of the 50% NiFe annealed at 2100°F.

The data of Figure 4 show additional relationships that appear to be generally true for magnetostrictively positive materials. The application of compressive write-in stress after field ($H\sigma$) results in substantially higher readout strain sensitivity than the reverse ON sequence when followed by either the $\bar{H}\,\bar{\sigma}$ or the $\bar{\sigma}\,\bar{H}$ OFF sequence. To a less important degree, removal of σ after removal of field ($\bar{H}\,\bar{\sigma}$) produces higher strain

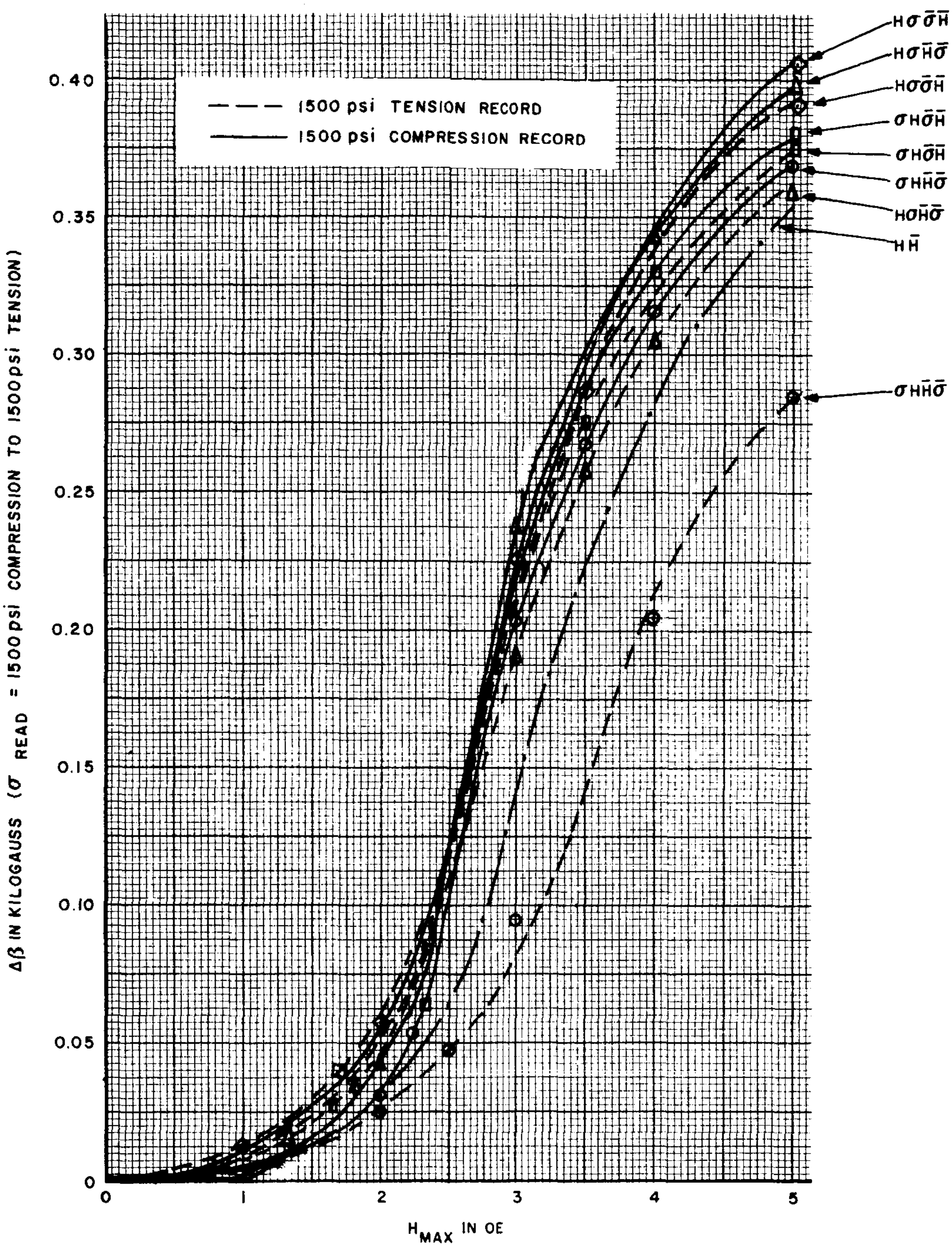


Figure 5. STRAIN SENSITIVITY OF PARTIALLY ANNEALED 50% NiFe AS A FUNCTION OF MAXIMUM FIELD AND WRITE-IN SEQUENCE

sensitivity than the reverse OFF sequence ($\bar{\sigma}\,\bar{H}$) when preceded by either the $H\sigma$ or the σH ON sequence.

Figure 4 also provides clearer insight into the possible advantages of the strain-biased medium previously proposed(1). For this case, the ZERO data level corresponds to $\sigma H \bar{H} \bar{\sigma}$ where σ is the tensile biasing stress which is cancelled ($\bar{\sigma}$) momentarily for write-in. The other sequences represent alternative sequences for the ONE write-in. Since the slope of the $\sigma H \bar{H} \bar{\sigma}$ curve as a function of H is very low, the readout strain sensitivity ratio becomes larger for the strain-biased medium where $H > 0.08$ oersted. S/N and signal levels therefore become less dependent on critical control of input level and uniformity of magnetic properties. Whether those advantages are offset by the higher field power required will have to be determined in overall systems analysis.

The misleading character of hysteresis loops is shown in Figure 6 for the fully annealed 50% NiFe. B_r actually decreases when compressive stress is applied. Consequently, the methods of Figure 4 represent a major advance in materials measurements for ferroacoustic storage.

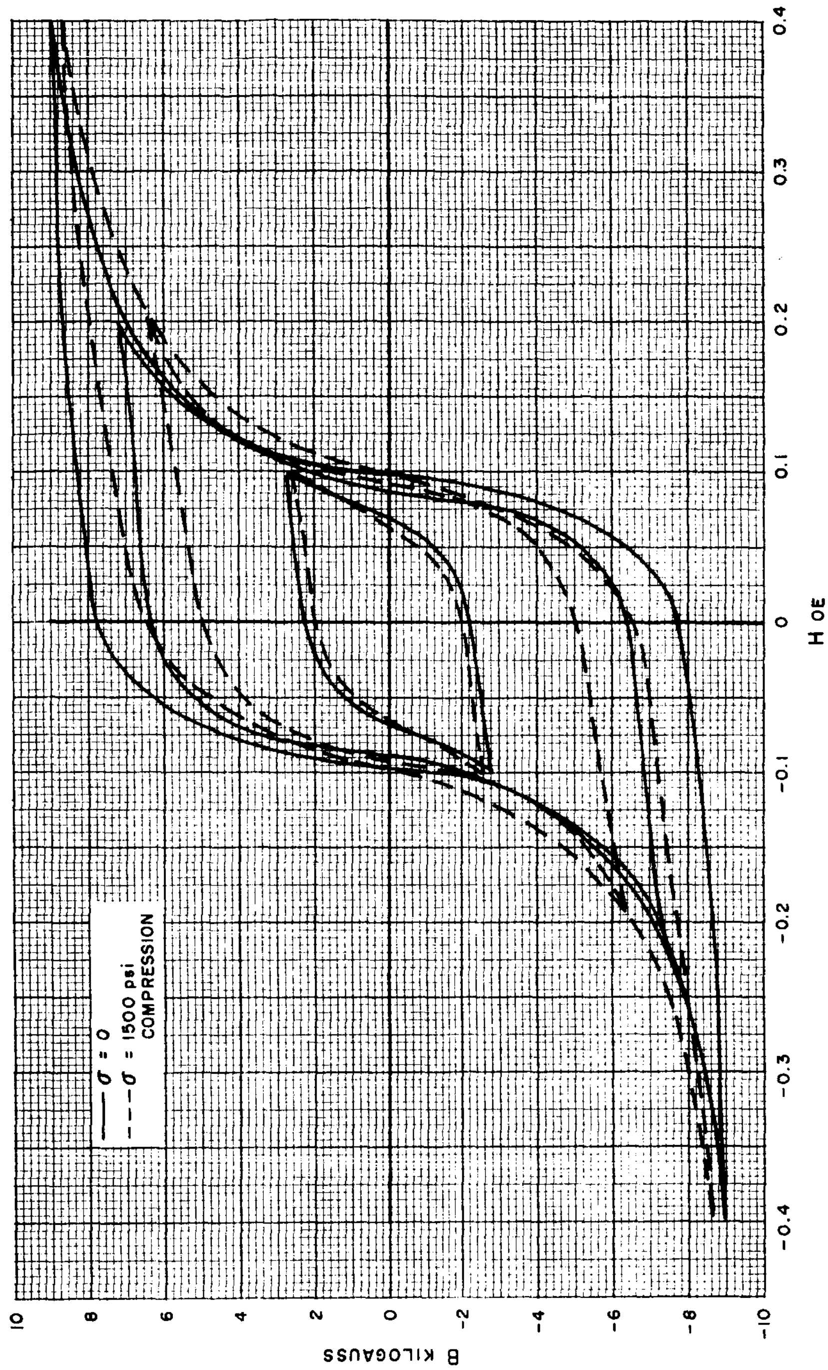


Figure 6. HYSTERESIS CHARACTERISTICS OF FULLY ANNEALED 50% NiFe

5.0 ACOUSTIC LINE ATTENUATION

Attenuation is a primary factor in the evaluation of mill processed media for ferroacoustic storage. The test fixture constructed and used for attenuation measurements consists of a properly-biased, fixed-position, magnetostriction receiving transducer and a driver transducer mounted on a slide which can be moved along the length of the line under test. The line can be suspended vertically from its end to avoid the need for intermediate supports which could otherwise add to the true line attenuation. To correct for non-uniformity of the line, a large number of measurements are made at peaks and valleys along the line. The method of least squares is then used to calculate the average slope of the curve for attenuation vs distance.

An attenuation of 0.16 db per inch was obtained for the transmission of 1-microsecond pulses in half-mil Orthonol strip. This attenuation is relatively small for an annealed magnetic material. Photomicrographs show average grain size to be 20 microns, also a relatively small value. Additional attenuation measurements were made with the strip lying on polyurethane foam and on a smooth mylar strip. Additional attenuations of only 0.02 db/in and 0.05 db/in, respectively, were observed.

6.0 MODEL STUDIES

Commercially available tubing and strip of thinner gauges are believed to offer relatively immediate prospects for the improved resolution and other advantages discussed in Section 2 of this report. Work during the past quarter, therefore, was concentrated on development of this approach rather than extended systems analysis based on the previously demonstrated storage characteristics for tubing of 15-mil OD X 2-mil wall. Three models were constructed using 50% NiFe tubing of 10-mil OD X 1-mil wall in the fully annealed (2100°F) and partially annealed (1000°F) conditions, and Orthonol 0.031 inch X 1/2-mil strip as processed for optimum cube-textured properties.

Tests of the partially annealed 50% NiFe tubing showed no improvement in resolution or S/N relative to previous data for 15-mil X 2-mil tubing. Drive current requirements, however, were approximately halved because of the smaller tubing cross section. One possible cause for the disappointing result is that there may be a significant difference in strain sensitivities which is not indicated in the cyclic hysteresis data which are essentially identical for the mill-processed 15-mil X 2-mil storage line and the partially-annealed 10-mil X 1-mil line. Quasi-static strain sensitivity data of the preferred form discussed under Section 4.3 can at present be acquired only with heavy samples having a wall thickness of the order of 20 mils. Heavy samples subjected to a straightening operation equivalent to that used in processing the 2-mil tubing are not available, however, and correlation between static and dynamic measurements is incomplete. A second more probable cause involves the new mechanical problems encountered in producing an acoustic-impedance match between the fine tubing and a driving horn. Alternatives considered include tubular horns, solid horns using a material of lower specific acoustic impedance such as aluminum, and use of a central non-magnetic conductor having a specific acoustic impedance equal to that of the tubing.

The technique actually employed consists of flattening the tube on one end so that its cross section changes gradually from the annular form to a 2-mil thick rectangle; a solid brass conical horn has 2 flats ground on opposite surfaces at its small end so that the resulting rectangular cross section matches the flattened rectangular tubing to which it is butt-bonded with silver solder. Small mechanical deviations from intended construction may be responsible for pulse broadening which prevents the expected improvement in performance.

The fully annealed 50% NiFe is coupled to the horn by inserting it in a dummy section of hard-drawn (effectively non-magnetic) NiFe tubing having 15-mil OD by 11-mil ID. Both tubes are then coupled to the horn using the same techniques found successful with 2-mil tubing. Tests on this model have just been started.

The thin Orthonol strip is tested in a model using a four-coil, sequentially-pulsed, magnetostrictive transducer in order to avoid the problems of mechanically-bonded transducers initially. This material saturates in the earth's field since it has a coercivity approximately one-fifth that of the tubing used in successful models. It is therefore, tested inside a solenoid which is adjusted to cancel the ambient field. No appreciable recording has been detected in model tests. A tentative explanation is discussed in Section 4.2.

7.0 CONCLUSIONS

1) The most immediate approach for improving ferroacoustic-storage resolution and speed is the use of mill-processed strip or ribbon which offers an effective thickness approaching one-tenth that of available tubing. Another advantage anticipated from this approach is the simplication of problems in coupling fine media to transducers.

2) The long-range development of planar thin-film configurations is believed more practical than the development of tubular forms because of anticipated simplifications in transducer-to-line coupling and in film deposition techniques.

3) Initial model-test failures to record on strip of half-mil thickness or to improve resolution with tubing having a 1-mil wall do not indicate basic problems. Use of differently processed strip materials and solution of the mechanical problems in coupling finer lines to transducers are required.

4) Half-mil, cube-textured Orthonol strip shows acoustical attenuation of 0.16 db/in, a relatively low value for annealed magnetic materials, and substantially softer magnetic properties than the 50% NiFe used previously in successful model tests. The results of unsuccessful model tests, however, suggest investigation of modified processing to improve strain sensitivity without degrading the other advantageous properties of the material.

5) Analysis of substrate considerations for thin-films indicates that glass will be required to avoid excessive thin-film strains due to differential expansion when ambient temperature control cannot be applied. Where temperature control is permissible, fused silica can be used to obtain minimum acoustical attenuation with resulting order-of-magnitude increases in line length and information capacity.

6) Comparisons of cyclic B-H data, or static magnetization curves, for the transverse induction of tubular isotropic material samples with and without axial stress give misleading or very tentative indications of material applicability for ferroacoustic storage. New quasi-static test procedures showing remanent strain sensitivity as a function of applied field for alternative sequences of field and stress are believed to provide definitive evaluations. On this basis, 50% NiFe, annealed at higher temperature than previously judged desirable, should permit substantial decreases in required driving stress and polarizing-field power.

7) Strain-sensitive anisotropic thin-films for ferroacoustic storage have basically different requirements from the anisotropic thin-films of low strain-sensitivity being developed for coincident-current memories. Moreover, characteristics showing a decrease in the easy axis coercivity with increasing transverse stress do not prove applicability of a film for ferroacoustic storage. Data showing B_r versus H_{max} for various stresses appear more definitive. Promising properties are provided by the first evaporated film tested.

8.0 PLANS FOR THE FINAL QUARTER

1) Improvement of techniques for coupling transducers to finer storage lines.

2) Completion of models and tests of:
   - (a) Fully annealed 1-mil tubing with the objective of reducing transducer stress and polarizing-field requirements, as well as improving resolution and speed.
   - (b) Cube-textured ultra-thin strip with final magnetic anneal to obtain uniaxial anisotropy for the purpose of further improvements in sensitivity, resolution, and ease of fabrication.
   - (c) Isotropic 0.3 X 4.5-mil ribbon, as an alternative to (b).

3) Quantitative systems analysis based on the best results of model tests.

4) Continuation of quasi-static measurements using the newly reported procedures for evaluation of storage materials and investigation of operating conditions.

5) Analysis of electrodeposited NiFe thin-films and improvement of special properties such as the strain sensitivity required in ferroacoustic storage.

9.0 IDENTIFICATION OF KEY PERSONNEL

The work described in this report was conducted in the Special Military Products Engineering department, F. A. Mitchell, Chief Engineer, and in the Physical Electronics Research Laboratory, Dr. C. E. Drumheller, Manager. The following personnel contributed to the work reported this quarter:

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APPROVAL

RESEARCH ON A FERROACOUSTIC INFORMATION STORAGE SYSTEM

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